(12) UK Patent Application (19) GB (11) 2 253 957 (13) A

(43) Date of A publication 23.09.1992

(21) Application No 9204647.3

(22) Date of filing 04.03.1992

(30) Priority data
(31) 4107207 (32) 04.03.1991 (33) DE

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(51) INT CL[5]
H02H 7/085

(52) UK CL (Edition K)
H2K KSD1B K234 K360 K452 K490 K512 K76Y K765 K768

(56) Documents cited
GB 2150774 A SU 001569856 A

(58) Field of search
UK CL (Edition K) G4G GAE, H2K KSD1B KSD1X
INT CL[5] H02H 6/00 7/085
Online database: W.P.I.



(54) **Protecting and determining operating life of electric machine**

(57) A method and apparatus for protecting, operating and displaying the remaining service life of motors or other electrical machines where such life is determined mainly by the thermal load, uses modelling devices, temperature sensors and devices for obtaining parameter values regarding the consumed service life and for predicting the remaining life. A measured value characteristic of the life consumption is obtained at defined intervals or intervals determined in dependence on the manner of operation of the motor or machine, and the measurements are compared with the elapsed life in order to determine the life consumption and thus make decisions regarding switching off or operating the motor during the next time interval on the basis of the parameters which determine the motor life.

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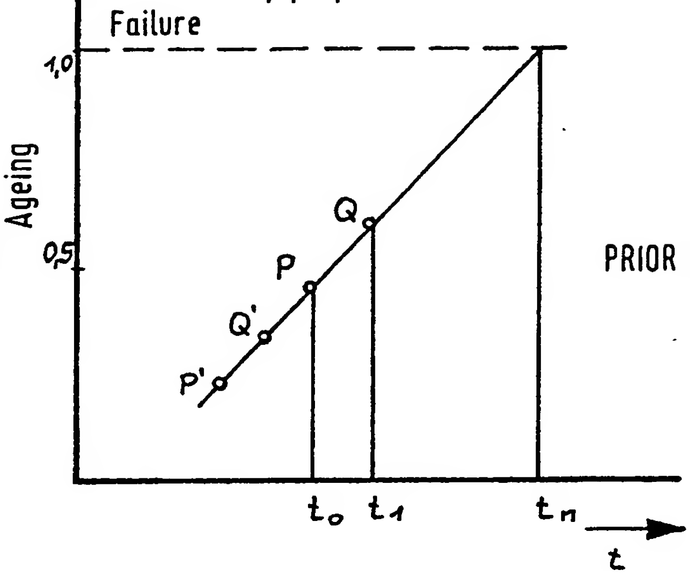
At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

FIG.1




PRIOR ART

FIG.2

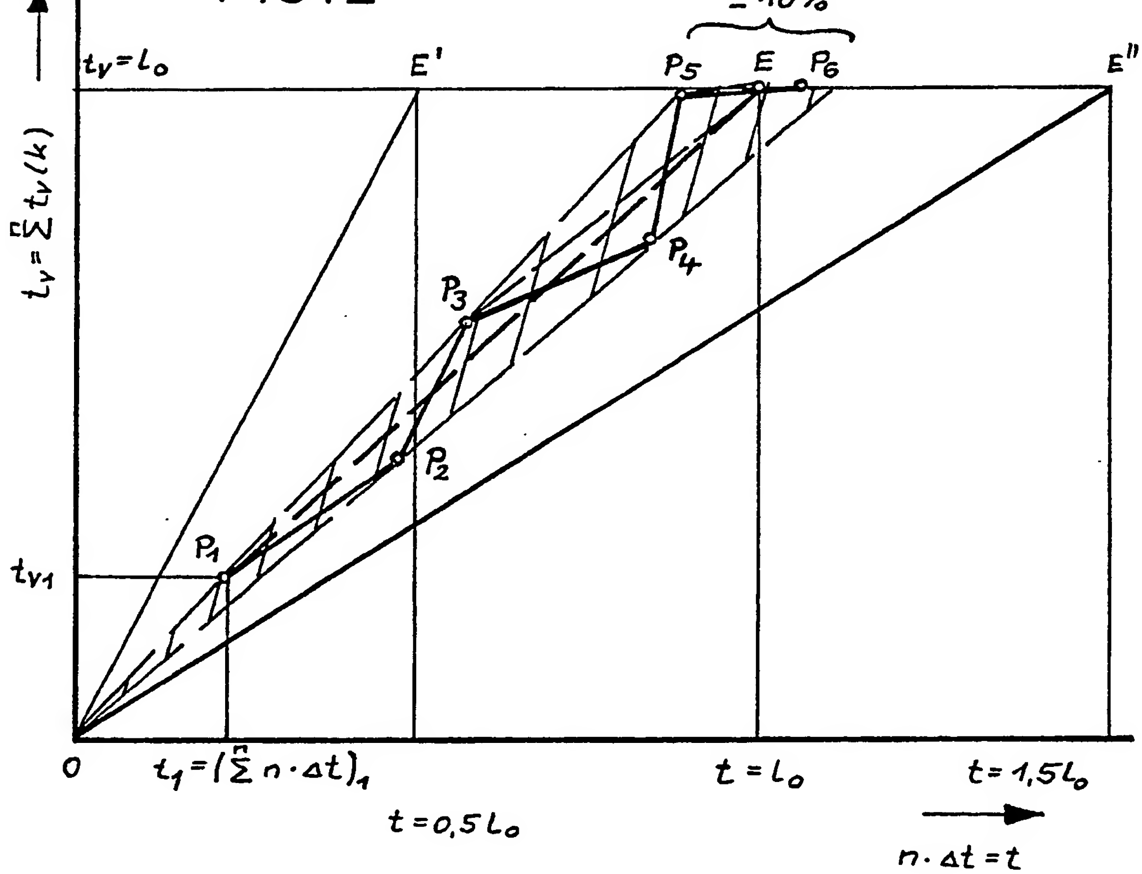


FIG. 3

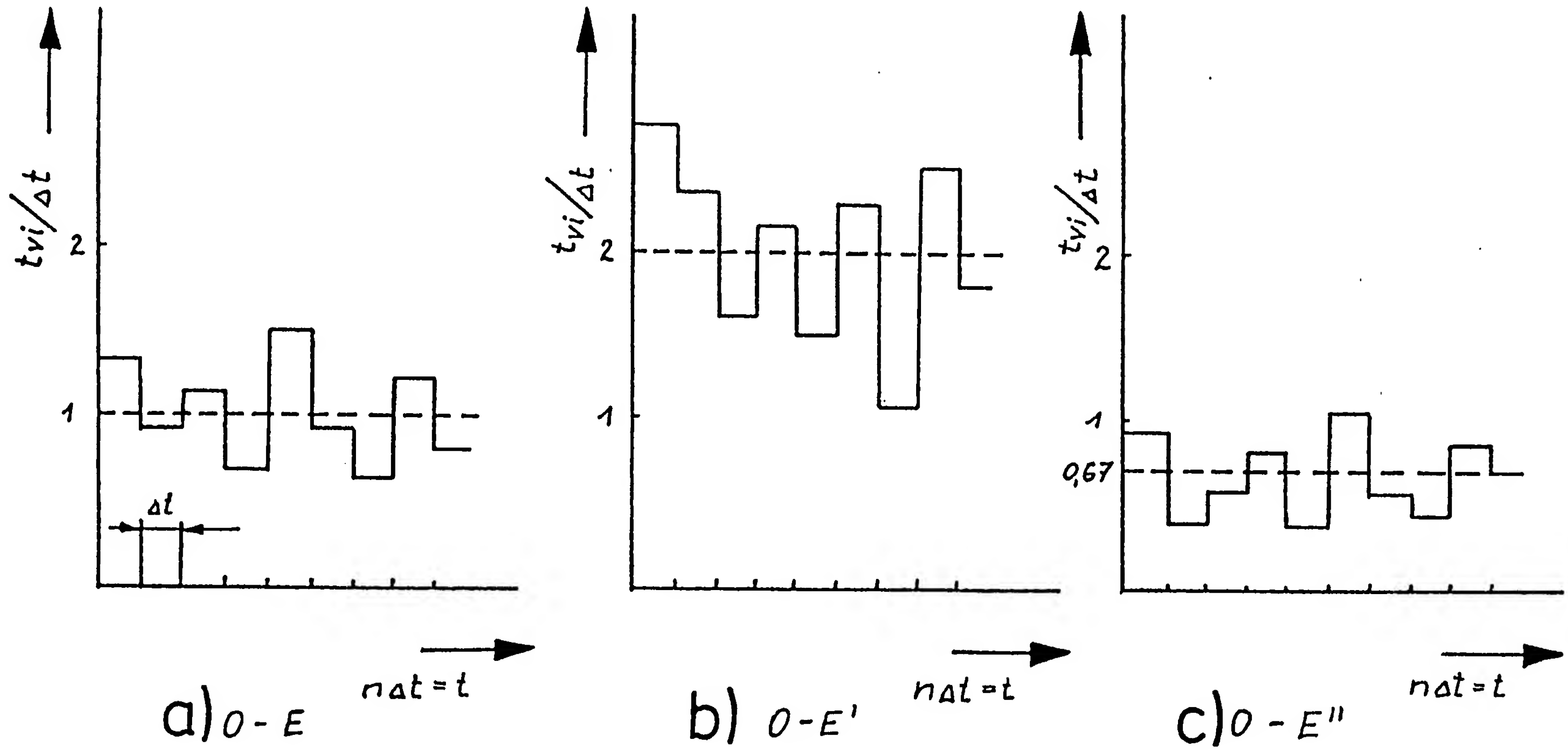


FIG. 4

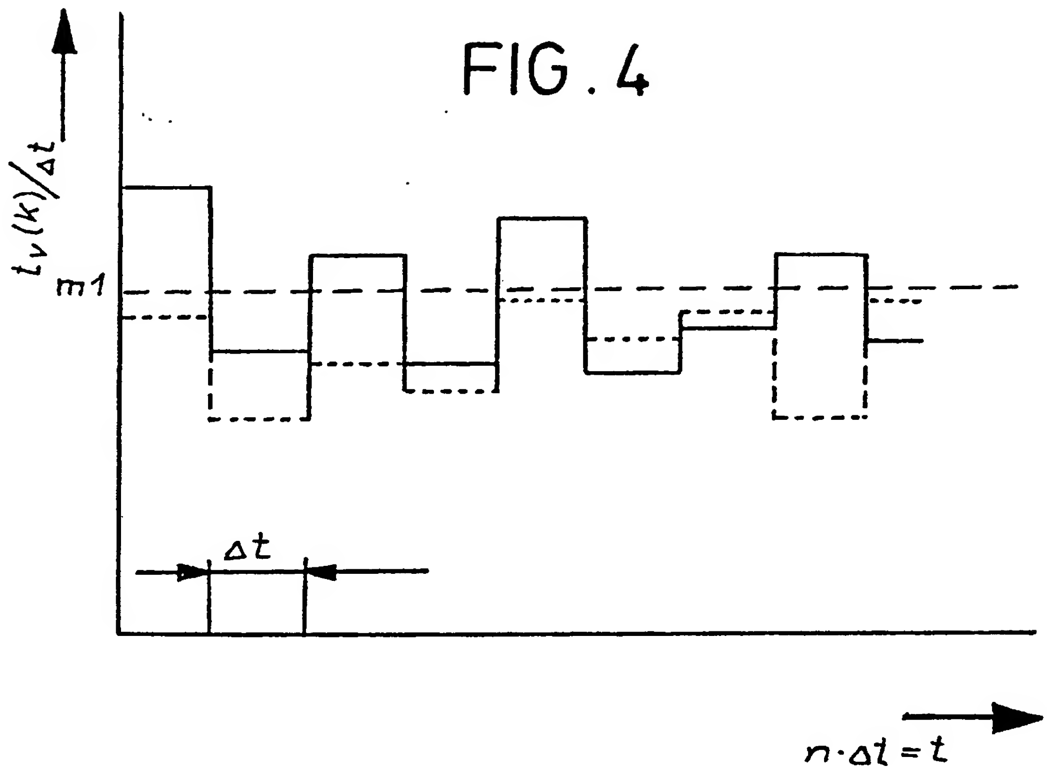
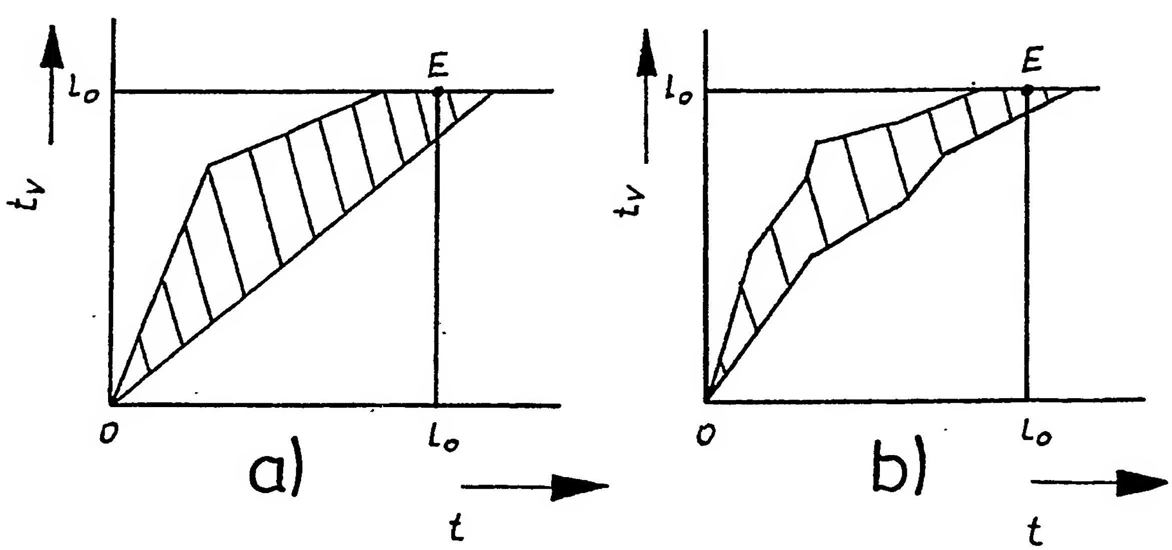



FIG. 5



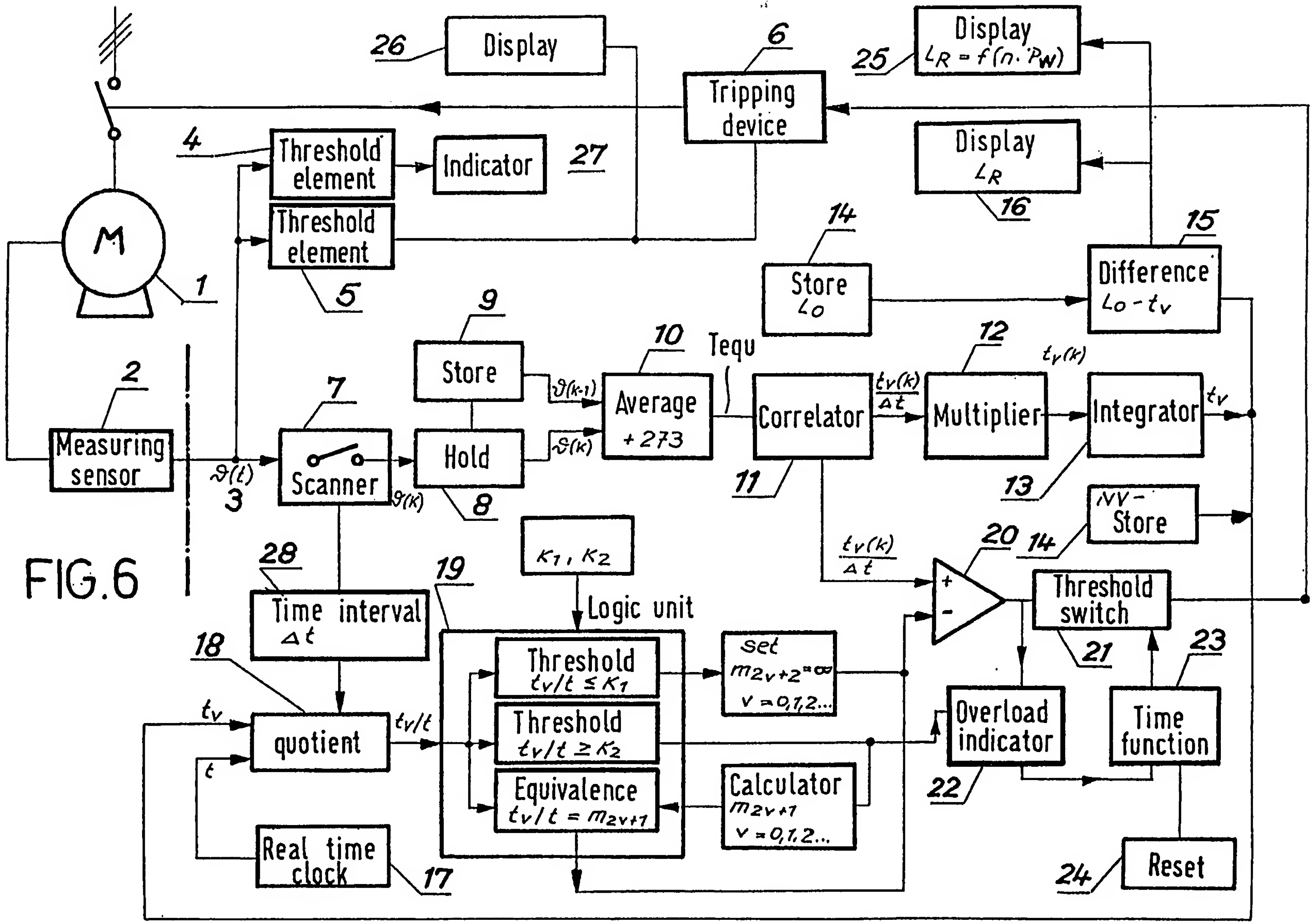

M
1
Measuring sensor
2
$\vartheta(t)$
3
Threshold element
4
Threshold element
5
Indicator
27
Display
26
Tripping device
6
Display $L_R = f(n \cdot P_W)$
25
Display $L_R$
16
Scanner
7
$\vartheta(k)$
Hold
8
Store
9
$\vartheta(k-1)$
$\vartheta(k)$
Average +273
10
Tequ
Correlator
11
Store $L_0$
14
Difference $L_0 - t_v$
15
$\frac{t_v(k)}{\Delta t}$
Multiplier
12
$t_v(k)$
Integrator
13
$t_v$
NV-Store
14
$\frac{t_v(k)}{\Delta t}$
20
Threshold switch
21
Time interval $\Delta t$
28
$K_1, K_2$
Logic unit
19
Threshold $t_v/t \leq K_1$
Threshold $t_v/t \geq K_2$
Equivalence $t_v/t = m_{2v+1}$
set $m_{2v+2} = \infty$ $v = 0,1,2...$
Calculator $m_{2v+1}$ $v = 0,1,2...$
Overload indicator
22
Time function
23
Reset
24
quotient
18
$t_v$
$t$
$t_v/t$
Real time clock
17

FIG.6

TITLE

A method and apparatus for protecting and operating electric motors and machines.

This invention relates to a method and apparatus for protecting, operating and displaying the remaining service life of motors, more particularly the windings of electric motors, the temperature of which is fairly near the winding temperature, or in general for electric motors or other electrical machines or electrical distribution systems, the life of which is mainly determined by the operating temperature.

An analysis of the workload on electric machines, more particularly three-phase synchronous motors, was made a few years ago and showed that these machines are loaded only to about sixty per cent of their rated capacity. This reduces the efficiency, particularly the power factor and results in higher current consumption, greater line losses or the use of thicker wire. Since many millions of such machines are in use, there is a wide potential here for saving electric energy or copper wire, if the under-loaded machines are replaced by electric motors operating at or near their rated loads. In such cases the change is always towards a smaller

motor and this results in further savings resulting from the reduction in the size of the motor, such as savings in copper windings, high-quality magnetic iron, insulating materials as example; these savings can be considerable. For example, in the case of the lower load range, a thirty per cent saving of weight can be obtained by replacing a sixty per cent loaded motor by a smaller motor which is one hundred per cent loaded under the same conditions.

These wide possibilities in saving electric energy and material have resulted in a variety of methods to increase and improve the load factor of electric motors. In the case of permanent operation, improvement means operation at the rated load at which the limiting temperature of the winding is approximately reached. The applicable rated life of the windings under these conditions is approximately known.

In most applications, however, particularly at the critical points for total operation, motors have to operate under widely fluctuating loads. Under these varying load conditions, an average optimum load factor can be obtained only if the motors are sometimes overloaded, the deficit or reserve being made up during the under-load phases. The winding temperature which can be used in the overload phases depends on the deficit

or reserves in the under-load phases. The upper temperature limit, therefore, need not be fixed but may vary or may be used up to a temperature which causes immediate failure of the winding. It is therefore impossible to apply the conventional method of motor protection, which is generally based on monitoring the fixed temperature limit. Corresponding remarks apply to other electrical machinery.

Hitherto, motors or other electric machines (such as transformers or distribution systems) the life of which depends mainly on temperature, have been protected by means of devices which either monitor the load current mechanically (bimetal) or by electronic means (electronic tripping devices) so as to simulate the temperature in the machinery to be protected and give or trigger a signal if a set limiting value is exceeded. In some cases, temperature sensors are directly incorporated in the winding and generate the triggering signal if a limiting temperature is exceeded.

All these devices have a common disadvantage in that they operate in accordance with a fixed temperature limit and without a memory function, so that the effect of the respective operating temperature on the service life - cannot be detected or taken into account.

The known devices have also hitherto been incapable

of detecting the effects of upper harmonics. Some suggestions to this end are known (DD-PS 247551) and cover the influence of these upper harmonics in proportion to the frequency or square of the frequency, but they can only handle non-recurrent processes.

It is also important, particularly in the case of synchronised and interdependent operating frequencies, to ensure that no machine, or particularly motor, is left unmonitored and fails unexpectedly. This means that it must be possible to monitor, display and signal the state of the motor and particularly the subsequent service life thereof. Consequently, the method of monitoring and protection must be based directly on the wear or degradation of the motor winding, which depends mainly on the temperature thereof.

One such wear criterion is the so-called "life consumption". US-PS 4525763 describes a method of this kind for protecting electric motors and predicting their life expectancy by determining the life consumption. The underlying idea of this method is illustrated in Figure 1 of the accompanying drawings.

At points P and Q, the thermal ageing of the motor winding is determined and the time is calculated by - linear extrapolation up to the failure line 1.0, by the rate of change in ageing between P and Q. Time tn is the

service life which the motor will reach if it continues to be loaded in the same manner as during the time between the point P and Q. This life is compared with the desired life and, in dependence on the result, a logic circuit decides whether the motor is to be switched off. This solution, however, still has the following critical disadvantages:

- The service life is extrapolated by using a straight line covering a range which is several powers of ten greater than the distance between the two points through which the line is drawn. As a result the possibly random events during an extremely small period of the order of seconds to minutes are transferred to the total service life, which is of the order of tens of thousands of hours.

- The extrapolation of service life requires corresponding circuits and calculations and is therefore very expensive.

- The method of extrapolation takes account only of the change in ageing between the points P and Q. The absolute position of the points, that is the previous history of the motor, is not taken into account when deciding to switch off. For example, the pair of points (P′;Q′) gives the same extrapolated service life as the pair P; Q) although the life situation at P′ and Q′ is

much more advantageous.

- The extrapolated life is always compared with the desired life, which is usually given by the manufacturer for normal conditions, but this cannot be used to calculate the remaining life which is of great interest to the user of the motor and is the life which the motor will have if it continues to operate under normal conditions for the rest of the time in service.

- The aforementioned method cannot provide a protection strategy which can be determined in advance and adapted to the typical load curves in a given case. The difficulties of choosing suitable criteria for protecting motors on the basis of service life have already been mentioned. The fundamentals of life consumption measurements and their importance for motor protection are discussed in Busch, R.:Motoruberwachung auf der Basis der Bestimmung des Lebensdauerverbrauchs (= monitoring of motors based on determination of life consumption) .Elektrie 43 (1989)8, pages A.287 to 289.

This method is based on purely thermal ageing of windings.

One of the objects of this invention is to overcome the aforementioned disadvantages of the known method and provide a protective apparatus which functions on the service life of the load, particularly the machine to be

protected and avoids excessive overloading which would immediately damage the motor and which also, particularly under widely varying loads, enables the load capacity of the protected machine to be fully used to obtain the previously described savings in energy and material resulting from a full work load. Another object is to provide a method whereby a motor or machine can be operated taking into account the desired service life, using simpler and more accurate means. Even when the service life is not predetermined or the load fluctuates widely, a signal can be given when a selected value of the service life is reached, so as to decide on subsequent operation.

According to a first aspect of this invention there is provided a method for protecting and operating electric motors or other electric machines or installations in accordance with the rated working life using operational models, temperature sensors and parameter values relating to the consumed working life and devices for protecting the remaining life, in which method a measured value characterising the life consumption is formed at intervals and either defined or determined in dependence on the manner of operation of the motor or electric machine to be protected, said value being compared with the operating time whereby the previous life consumption

is determined and used to make a decision regarding the protection or operation of the motor during the next time interval, on the basis of the measured parameters determining the motor life.

According to a second aspect of this invention there is provided an apparatus for carrying out the method according to the preceding paragraph and effecting control of the operation of a motor or machine so as to obtain the scheduled service life and to obtain maximum efficiency under varying loads, in which apparatus a quotient is formed from the total operating time (t) and the life consumption
(tv), the resulting output actuating a comparator which, in the event of an increased load which does not allow the scheduled life to be reached, generates a signal and disconnects or switches off the motor or machine by means of a tripping device either immediately or after a delay controlled by a time function element.

This invention therefore provides a method and associated hardware or equipment which, starting from a single measurement of the life consumption, compares it with the elapsed time before the time in which the life consumption was measured, and calculates decisions - regarding the protection and/or operation of the motor on reaching this time and in accordance with previously

calculated ageing values of the motor winding, and simultaneously calculates criteria for protecting and operating the motor subsequently, in dependence upon its previous history. These criteria apply until the life consumption reaches another value, which can also be freely calculated in advance, at a time when the criteria for protection and operation of the motor are re-calculated for the next period. The criteria are calculated in a manner whereby the desired life or its expected value are ensured or reached with predetermined accuracy. The life consumption, for any desired values of the factors determining it, is always calculated as if based on normal values of these factors (in the case of temperature, for example, the limiting temperature of the insulating material used) so that, simply by obtaining the difference between the life consumption and the normal life published by the manufacturer of the winding, it is possible to calculate the life which will remain if the motor continues to operate under normal conditions, that is at the rated load, starting from the time under consideration. In order to estimate these normal service lives, the user of the motor has much more experience than for estimating the service life under other conditions. More particularly, when the load varies widely (a main application of life-oriented motor

protection or operation) it is more helpful for the user to know this value than to know the service life which will remain if the motor continues to operate in the same manner as in the preceding measured interval, even though this value can also be determined by the method proposed here.

This invention will be explained in more detail with reference to an example of the method and an embodiment of the apparatus for carrying out the method and with reference to the accompanying drawings, wherein:

Figure 1 shows a graph of a known method for determining life expectancy and already referred to,

Figure 2 shows a graph for determining life consumption,

Figure 3 shows three examples of variations in life consumptions, a), b) and c),

Figure 4 shows a graph of time variation of life consumption from point $P_1$ in Figure 3,

Figure 5 shows two examples a) and b) where pre-set values are in accordance with expected load variations, and

Figure 6 shows in block schematic form an embodiment of apparatus according to this invention.

Example of the Method

Figure 2 shows a service-life diagram in which the life consumption, determined by the temperature and optionally by the voltage and mechanical load on the winding, using the appropriate life function, is plotted in dependence on time. The life consumption is equal to the sum of the life-consumption values during n intervals of length $\Delta t$. The values tv (K) can either be calculated from the winding data and the stress factors (temperature, voltage and mechanical load) or taken from a table which can be stored. The possible variation in time in the stress factors within the interval $\Delta t$ must be taken into account.

If the plotted point given by tv and $t = n. \Delta t$ moves along the straight line O-E, the motor will reach the life Lo (normal life) of for example 30,000 hours, which is the usual aim. If the point moves along the line O-E', the life will be 0.5 Lo (15,000 hours in the example) whereas if the point moves along the line O-E'', the life will be 1.5 Lo, (45,000 hours).

Figure 3, for the three cases given, shows the possible variation in time in the life consumption relative to an interval length $\Delta t$. The horizontal broken lines are the average values of tv (k)/$\Delta t$ to be obtained after a given number of intervals.

In order to obtain switching points or decision points defined during the progress in the life diagram in Figure 2, a decision can be made to move within regions defined for example by the lines 0.9 Lo ($k_1$ = 0.9) and 1.1 Lo ($k_2$ = 1.1) (see shaded region). If for example the motor reaches the point $P_1$ either the load on the motor can be reduced or the motor can be switched off (the life consumption in this case is tv = 1.11t = 1.11n. $\Delta$t or tV/t = 1.11).

Allowing for the position of point $P_1$ a value $m_1 = (tv(k)/\Delta t)1$ is calculated such that if this value is permanently kept to in future or if this value is kept on average, the point will move along the line $P_1$ - E being directly towards the desired service life $L_0$. In the present case, the value calculated at the point $P_1$ is

$$m_1 = \frac{1-(\overset{n}{\Sigma} t_v(k))_1/L_0}{1-(n \cdot \Delta t)_1/L_0} = \frac{1-\dfrac{t_{v1}}{L_0}}{1-\dfrac{t_1}{L_0}}$$

From point P onwards, two methods of operation are possible. Either care is taken that during the remaining operating time the values tv $(K)/\Delta t$ will on average be equal to $m_1$, or $m_1$ is set as the upper limiting value and the motor is switched off if this value is exceeded. The variation in time of the relative life consumption, starting from point $P_1$, is shown in Figure 4 for both these cases.

The last mentioned case can be achieved more easily and will therefore be further described here. Since the values of tv $(k)/\Delta t$ are always less than $m_1$, the plotted point in the diagram in Figure 2 moves towards the point $P_2$ at which the next decision needs to be made regarding the permissible life consumption in the next period. At this point we have:

$tv = 0.91\ t = 0.91\ n\Delta t$. The life situation, therefore, has improved. There is no reason not to increase the load during the subsequent period. In this case, there is no need to limit the values $tv(k)/\Delta t$, (although there is a limitation as regards the winding temperature, which must not exceed the value at which the thermal part of the life function still holds), so that the plotted point can move along a curve of any desired shape and steepness until the point $P_3$ is reached. At this point it is again necessary to prescribe the correct

direction of motion, which can be done by re-calculating and setting a value

$$m = \frac{1 - \dfrac{t_{v3}}{L_0}}{1 - \dfrac{t_3}{L_0}}$$

which determines the direction of motion P-E in the same manner as for the point $P_1$.

The strategy for designing the trip criteria at point $P_4$ is the same as at $P_2$, whereas $P_5$ is the same as for $P_1$ or $P_3$, etc. In this manner the motor reaches its planned service life within the tolerance range plus ten per cent. Of course, the width of the tolerance range, being the angle between the lines bounding the shaded area and the shape of the lines, can be chosen or pre-set as required. The pre-set values can be in accordance with expected load variations or other criteria. Figure 5 shows two examples.

The aforementioned method is based on the concept of operating the motor during the service life, so that by adjusting the load, movement progress along the line O-E

or O-E′ or O-E′′ in Figure 2. To this end, the actual value of the calculated life consumption must be linked by a control system with the set value given by the curve in the life diagram (in Figure 3 the values are 1 or 2 or 0.67). The generated adjusting signal alters the load on the motor as required, in dependence on the actual value. One example is a conveyor belt, the load on which is controlled by adjusting the slide valve in a loading bunker in dependence on the life consumption of the drive motor.

Figure 6 shows an embodiment of an apparatus for protecting a motor (an electric machine in this example). A motor 1 is subject to purely thermal ageing, as in the case of low-voltage machines, so that the winding temperature or the temperature of the hottest point in the winding must be incorporated in the circuit. This temperature information, as shown in Figure 6, is reproduced either by a temperature sensor or a generator device 2, which reproduces the temperature signal for the thermal load on the basis of electrical parameters of the machine, such as the current and voltage, and other factors such as ambient temperature, motor speed, and external cooling. The temperature signal 3 is fed in across the line A shown in Figure 6. The design of the rest of the circuit according to the invention, shown to

the right of the line A, is independent of the manner of determining the temperature. If the temperature reaches a first adjustable limiting value, the threshold element 5 and the tripping device 6 gives the alarm. If the temperature reaches a second limiting value, above which the winding will suffer irreversible damage, the winding is disconnected from the power by the threshold-value element 5 and the tripping device 6, the immediate switching-off being optionally displayed by 26. Otherwise the temperature of the machine is scanned at time intervals t in correlator 11 and the interval limiting values $\vartheta(k-1)$ and $\vartheta(k)$ are used to calculate that (constant) equivalent temperature Tequ which brings about the same life consumption as during the normal variation of temperature in the time interval. By means of a functional correlation (store or mathematical function) based on the life function applicable to the winding, element 11 calculates the value tv $(k)\Delta t$ which describes the ageing of the motor relative to the elapsed operating time. A multiplication stage 12 then gives the actual life consumption, which is summed in an integration stage 13 and permanently stored in a store 14. In difference element 15, the difference between the cumulative life consumption tv and the normal life Lo is obtained and input into the store 14 or as required

at a given load, thus giving the remaining life of the motor which will be reached if it operates under normal conditions (at the limiting winding temperature) during the rest of the operating life (in Figure 2 this quantity corresponds to the vertical distance between the plotted point and the horizontal line $tv = L_o$). This very important value is displayed at 16. Alternatively, this value can be used in display 25 for showing the remaining service life $L_K$ at various loads and in the form of a multiple n of the rated load $P_N$ of the motor 1.

Also, tv is processed, together with the time in a real-time clock 17, in a quotient-forming device 18. The output signal from the real-time clock 17 is the time during which the life consumption is not negligible during the entire period of operation of the motor. It can therefore be switched off during phases when the winding temperature is very low.

The calculated quotient tv/t characterises the position of the plotted point in the life diagram, and this value must therefore be processed in a decision logic unit 19. If the lower limiting line determined by $k_1$ is reached or the value becomes lower still, the comparator will be influenced so that even at very high values of $tv(k)/\Delta t$, the threshold value for tripping will not be reached. If the upper limit in the life

diagram, determined by $k_2$, is reached or exceeded, there will be a signal or display, for example on 22, and if the overload persists the motor 1 will be disconnected by the threshold-value switch 21, either directly or after a delay via the time function element 23, unless the re-set key 24 is used. At the same time the inverting input of comparator 20 is connected so that the values tv $(k)/\Delta t$ are limited in accordance with the calculated value of m.

Since, as described, all parameters can be freely fed in, the result is a very flexible and relatively inexpensive protective system capable of efficiently protecting a motor which has a high work load and, in order to save energy and material, has to operate in phases when the winding temperature is considerably above the conventional limit. Since most of the functions shown in Figure 6 can be implemented in a microcomputer, the protective or control device can be made at a particularly low cost by using a single chip microcomputer or micro-controller.

For simplicity, Figure 6 does not show those control functions which are already described in the text.

CLAIMS

1. A method for protecting and operating electric motors or other electric machines or installations in accordance with the rated working life using operational models, temperature sensors and parameter values relating to the consumed working life and devices for protecting the remaining life, in which method a measured value characterising the life consumption is formed at intervals and either defined or determined in dependence on the manner of operation of the motor or electric machine to be protected, said value being compared with the operating time whereby the previous life consumption is determined and used to make a decision regarding the protection or operation of the motor during the next time interval, on the basis of the measured parameters determining the motor life.

2. A method according to Claim 1, wherein at a given time or at the end of a measurement interval for the motor or the electric machine, the intermediate life consumption is displayed for an arbitrary load or for fixed loads and as a multiple of the rated load.

3. A method according to Claim 1 or 2, wherein when the life of a motor or electric machine reaches a pre-set value, the measured life consumption is used to adjust the subsequent loading on the output or the drive so that the desired life is reached.

4. A method according to Claims 1, 2 or 3, wherein means are used to obtain a temperature signal characterising the thermal load on the motor or electric machine to be monitored, the temperature signal being scanned during a unit of time and an equivalent temperature determining the life obtained therefrom, said temperature being used in conjunction with a stored function or mathematical equation to obtain a value which determines the ageing of the motor or electric machine relative to the preceding operating time, the resulting life consumption being calculated in a multiplication stage and integrated and stored.

5. A method according to any one of Claims 1 to 4, wherein the calculated and the stored consumed life value are compared with a normal life by forming a difference value used to obtain and display the remaining life if the motor or machine is subsequently operated at the same or a different load.

6. A method according to Claim 3 or 4 when incorporated into a larger control system for an industrial plant.

7. An apparatus for carrying out the method according to Claim 1, and effecting control of the operation of a motor or machine so as to obtain the scheduled service life and to obtain maximum efficiency under varying loads, in which apparatus a quotient is formed from the total operating time (t) and the life consumption (tv), the resulting output actuating a comparator which, in the event of an increased load which does not allow the scheduled life to be reached, generates a signal and disconnects or switches off the motor or machine by means of a tripping device either immediately or after a delay controlled by a time function element.

8. An apparatus according to Claim 7, wherein the parameters for determining the state of operation are displayed by display units.

9. An apparatus according to Claims 7 and 8, wherein the temperature signal is fed directly to threshold-value elements, one of which, at a predetermined set temperature of the monitored motor or machine, generates a signal via display means whereas the other threshold-

value element immediately switches off by means of a tripping device and simultaneously produces a signal before the temperature of the motor or machine reaches that critical value which may cause irreversible damage.

10. An apparatus according to any one of Claims 7 to 9, wherein the entire apparatus and the individual components or functional units are incorporated on a single-chip microcomputer.

11. An apparatus according to any one of Claims 7 to 10, wherein the apparatus has a modular construction whereby individual functions can be used in any desired combination.

12. An apparatus according to any one of Claims 7 to 11, wherein the individual components and the required peripheral devices are incorporated in a unit which can co-operate or be combined with switchgear or process-control devices.

13. A method for the operation of electric machines carried out substantially as described herein and as illustrated by Figures 2 to 6 of the drawings.

14. An apparatus for the control and operation of electric machines constructed and arranged to function substantially as described herein and as illustrated and exemplified by the drawings.

# Patents Act 1977
## Examiner's report to the Comptroller under Section 17 (The Search Report)

Application number

9204647.3

**Relevant Technical fields**

(i) UK Cl (Edition K ) G4G (GAE)
H2K (KSDIB,KSDIX)

(ii) Int CL (Edition 5 ) H02H (6/00,7/085)

Search Examiner

D C BRUNT

**Databases** (see over)

(i) UK Patent Office

(ii) ONLINE DATABASES:WPI

Date of Search

19 MAY 1992

Documents considered relevant following a search in respect of claims 1-14

| Category (see over) | Identity of document and relevant passages | Relevant to claim(s) |
|---|---|---|
| A | GB 2150774 A (GENERAL ELECTRIC) whole document | - |
| A | SU 1569856 A (IVAN POWER) | - |

SF2(p) 1SF - c:\wp51\doc99\fil000407

| Category | Identity of document and relevant passages | Relevant to claim(s) |
|---|---|---|
| | | |

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X: Document indicating lack of novelty or of inventive step.

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